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HUMAN ABILITY TO WORK UNDER DECREASED AIR PRESSURE

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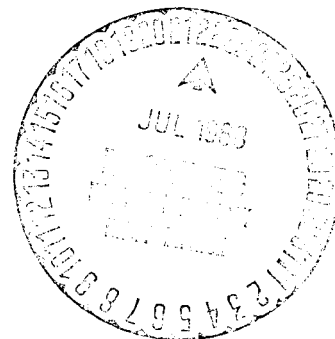
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HUMAN ABILITY TO WORK UNDER DECREASED AIR PRESSURE¹

R. Margaria

ABSTRACT. Laboratory tests were carried out under decreased atmospheric pressures. Test subjects worked at their own rates on a cycle ergometer which partially actuated a generator; the square of the amperage difference was used as a measure, converted into kilogram meters per second. Pressure at 5000 meters prevented 3 out of 4 subjects from accomplishing his set goal of 10 minutes work (after 4 trials). Only one was able to complete a test at 7000 meters. Work in these high atmospheres led to euphoria; lack of motor, perception and memory abilities; fainting conditions. Mimetic muscular fibrillation and spastic contraction of other muscle groups was generally noted. Respiration remained regular and deep, though slow. Anoxemia works first on the muscles and then on the central nervous system.

Introduction and References

It is generally known that at high altitudes muscular work is connected with much greater effort than on the level under normal atmospheric pressure; under these conditions even relatively little intensive muscular work causes significant alterations in respiration, changes which would occur at sea level only after extremely hard work, and which cannot be continued over a long period of time since fatigue sets in quickly; as the same disturbances, which are characteristic of mountain sickness, set in very easily, one can actually believe that mountain sickness is caused in part by fatigue.

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De Filippi [1], who took part in the expedition of the Duke of Abruzzi to the Karakorum Range in the year 1909, even advocates the view that mountain sickness can be ascribed solely to muscular stress. The basis for this belief was the observation that up to heights of 7500 meters above sea level an acclimatization can be fully accomplished, following which healthy individuals who attain these heights gradually can remain in the best health for a long time, as if under normal air pressure.

¹ From the Physiological Laboratory of the Royal University, Turin, Professor A. Herlitzka, Director.

² Numbers in the margin indicate pagination in the foreign text.

Therefore, only muscular work is made difficult at these altitudes; aviators report noticing a great muscular weakness when they fly at great altitudes, even when they must accomplish an extremely simple task, such as taking a photograph, and Major Hingston [2], in the last expedition to Mount Everest in the year 1924, observed that at altitudes over 6000 meters muscular work did not evoke actual fatigue as under normal atmospheric pressure, but rather the feeling of burden and lassitude, which disappeared after a brief rest.

The fact that work capability, that is the maximum output of work which an individual can perform in a specified time, decreases with lessening air pressure is clear when one thinks of the role which oxygen plays in the phenomena which accompany muscular work.

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According to the researches of A. V. Hill [3,4], and Meyerhoff, muscular contractions occur in an anerobic state, so that the energy is developed at the cost of the transformation of the glycogen, which is found in the muscle, into lactic acid, which then in the presence of oxygen is in part oxidized and in part retransformed into glycogen.

The oxidation process of the lactic acid and the reproduction of the glycogen will naturally progress with a velocity which is a function of the concentration of the oxygen and the lactic acid -- if we simply agree with Barcroft [5], that it is a physical-chemical system which obeys the law of mass effect. Consequently, if the concentration of oxygen decreases, the oxidation of the lactic acid and its retransformation into glycogen proceeds more slowly. And since the concentration of lactic acid in the muscles and the blood cannot exceed a certain limit without fatigue and inability of the muscles to contract setting in, it follows that fatigue as a result of work will be quicker the lower the partial pressure of the oxygen becomes.

The long-known fact that fatigue in isolated muscles develops much more quickly if it is located in an atmosphere weak in oxygen than in one rich in oxygen affords a confirmation of this assumption in addition to the observations described above, which were made on the entire organism (Fletcher [6]).

Observations made on human beings, however, are sparse and, although incontrovertible, are almost all based upon subjective feelings of decreased work capability without our knowledge as to how much this work capability declines as a function of this decrease in atmospheric pressure. The study of "work capability" under decreased atmospheric pressure was much neglected, while the conditions under which a specified task was accomplished (changes in breathing environment, oxygen consumption, modifications in breathing, pulse, etc.) have been very thoroughly researched.

The only quantitative determination of work capability at low atmospheric pressure which I have found in literature are those of A. Mosso [7], which consist of ergographic measurements conducted on the same acclimatized person at sea level and in the Queen Margherita Hut on Monte Rosa (4560 meters above sea level); he made the observation that, while the form of the ergographic

curve in both experiments did not change, the work which was done in the Queen Margherita Hut was a little lighter, viz. 2.828 kg/m as compared with 3.48 kg/m which was done in the experiments at Turin.

This single observation of Mosso is only based on fatigue in a single muscle and does not take into consideration the general evidences of fatigue which occur when one places a large part of the muscles in the body into action.

I have attempted to determine how great the maximum work capability of a human being is when several muscle groups participate in work, as is true in most cases in mountain climbing or in flying.

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Arrangement of Experiment

The arrangement used by me consisted of having persons who had voluntarily made themselves available and who had been fully instructed about the purpose of these experiments perform the maximum amount of work which they could accomplish at their own pace in a definite time period (10 or 15 minutes) on a cycle ergometer and recording the accomplished work at various times up to the completion of the experiment.

The wheel of the ergometer, which was set in motion by a chain drive like the rear wheel of an ordinary two-wheel bicycle, was connected by a belt to the axle of a generator which was independently activated by a storage battery. When the actuation was altered, the resistance caused by the rotation also changed proportionally to that from the generator, and with constant actuation the electromotive force on the brushes was proportional to the rotation speed of the generator.

The characteristics of the generator were as follows: 25 volts, 12 amperes, 1200 rpm. The brushes were short-circuited by an ordinary copper wire of very low resistance, so that a precision ammeter (0 - 3 A) which was laid parallel to the brushes, showed the alterations in current during the experiment with sufficient precision. The square of the amperage was selected as the measure of work, and from this value the measurement in kilogram meters per second was converted; I was able to do this by the knowledge of the working level of the entire bicycle-generator system, which was calibrated by means of a motor of known working level.

The test subjects were all practiced in this work, which accounts for the regularity of the curve and for the constancy of the values which were obtained with each test subject under normal atmospheric pressure before the experiments under reduced air pressure began.

All test persons had a certain familiarity with the pneumatic chamber; they were not informed of the negative outcome of the test under extremely low pressures which had been received from others, in order to exclude the influence of the psychic factor in the performance of the work.

Work was begun as soon as the desired pressure reduction was achieved; at the end of the work the test persons were completely exhausted so that they often had to stretch out on the floor with completely flaccid muscles in order to be able to change their clothes. In some experiments conducted at 24° in the Margherita Hut, a weight loss of 400 to 500 grams was noted, mostly as a result of perspiration.

Three of the test persons were students 22 years old; the fourth Mar., 27 years old; all were of normal constitution, and in complete health at the time of the experiments.

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Results of the Experiment

In the curves published herein, I am summarizing the entire experiment results for each person; I have entered the potential in mkg per second as a function of the time elapsed from the beginning of the work. The values which refer to the experiments conducted under normal barometric pressure are mean values from at least three tests, one of which was made at the end, after the experiments at decreased atmospheric pressure. Of the latter, only one experiment was done for each pressure level; they were conducted chronologically between the experiments at normal atmospheric pressure.

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Only the test person Mar. [transl. note: This is an abbreviation for the name, not the noun for a male] was not able to complete the work for the prescribed length of time (10 minutes) at 5000 meters (406 mm Hg) the first time, since he stopped after 6 to 7 minutes, completely exhausted; he had to repeat the test four times before he was able to complete the 10 minutes.

The experiment at 7000 meters (316 mm Hg) was only completed by one test person, since the others could not stand such low pressure. Of the others, only Gol. came to 316 mm Hg without difficulty; when questioned about his physical condition, he answered that he felt good and declared himself ready to carry out the work. I gave the signal to begin; but Gol. was only able to complete a few pedal revolutions in fifteen seconds for an output of 8 to 10 kgm-sec when he stopped. He was pale, had sleepy eyes, and slow, shallow respiration; clonic contraction of a convulsive nature occurred in the arms and legs; between one contraction and another he began again and again to turn the pedals slowly without understanding my repeated instructions to stop. Restoration to normal air pressure was begun immediately; at a pressure of 450 mm the test person seemed to wake up and at 520 mm he had completely regained his normal appearance. He had severe pains in his ears, because during the entire compression period up to that moment he had not swallowed and he asked me why I had not given the order to begin work; he was quite astonished when I told him that he had not been feeling well and we had returned to normal pressure; he himself recalled nothing about it.

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At a pressure of 330 mm (about 6500 meters) the other two test persons exhibited severe pallor and cyanosis of the lips, and since they did not even have the strength to remain sitting on the bicycles, they stretched themselves out, completely asleep, in a corner on the floor of the chamber; their faces

took on a completely collapsed appearance, and they were able to grasp what was said to them from outside only with great effort and after a long delay. For this reason, we decided against any further decrease in pressure.

After they had come out of the chamber they declared that they felt completely well and were very surprised that I would not expose them to a more severe decrease in pressure. They could not in the least account for the state of dullness, the extreme weakness and almost unconsciousness in which they had found themselves at the lowest pressure achieved.

The symptomatology of these test persons had many similarities to that of those two test persons who were brought to a pressure of 115 mm Hg in an atmosphere of pure oxygen in our own laboratory by Senior Staff Doctor Talenti [8], insofar as in both cases the test persons came to the threshold of unconsciousness and not only did not notice their abnormal condition, but actually were in a euphoric state.

A further point of similarity between the symptomatology of pressure reduction in an air atmosphere and of that in an oxygen atmosphere is in the muscle contractions, which were more or less limited to some muscle groups. Talenti had specifically noted fibrillary contractions of the mimetic muscles, which I was also able to observe, since I had the opportunity to sit in on his experiments. In my experiments the contractions which occurred with Gol. were much more severe, since they were true contractions of a convulsive nature of entire and extended muscle groups. In the experiment conducted by me at 7000 meters, I myself noticed a tension of the mimetic muscles and somewhat disagreeable spastic contraction of the hypotenar muscles of the right hand, which I could not eliminate either by altering the position of the hand or by any other means.

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However, we find one difference between the experiments in the air and in oxygen, and that is in reference to respiration; while in Talenti's experiments the test persons inspired increasingly smaller volumes of air and at the end actually ceased to breathe without yet losing consciousness, the test persons in my experiments breathed completely normally, even at the lowest air pressure. The two test persons Man. and Gya. who only reached a fictional altitude of 6500 meters, certainly did not find themselves in better condition than Talenti's test persons, so that they had to throw themselves on the floor, completely exhausted, while the latter were still able to sit on a chair. In spite of this, they still had a regular and deep, even if slow (10 to 12 per minute) respiration, so that it could be observed with certainty that the lung ventilation, even though it was not possible to measure it, still definitely reached much higher levels than in Talenti's experiments, in which these values amounted to about 4 liters in one minute. Also, while in the experiments in pure oxygen up to 115 mm Hg the declination in lung ventilation was the principle and most serious feature, this occurrence was not to be noticed in the experiments in an air atmosphere up to 320 mm Hg.

This fact demonstrates once again what has already been determined by me elsewhere in animal experiments [8] and by Talenti [9] on the basis of human experiments, that actually the decrease in air pressure in an air atmosphere cannot be equated with that in an oxygen atmosphere, that therefore the reduction of the partial tension of oxygen alone is not sufficient to explain the hypobaropathy, as those adherents of anoxemia as an explanation of mountain sickness have claimed (Barcroft [5], Haldane [10]).

Discussion of the Results

If we now go over the curves of the work accomplished by the individual test persons at various pressures for a check, we see first of all that these curves show an initially rapid decrease in work output until it reaches a constant value, which is maintained until the end of the experiment. All the curves differ from one another only insignificantly in shape, but considerably on the other hand in the height of the constant work.

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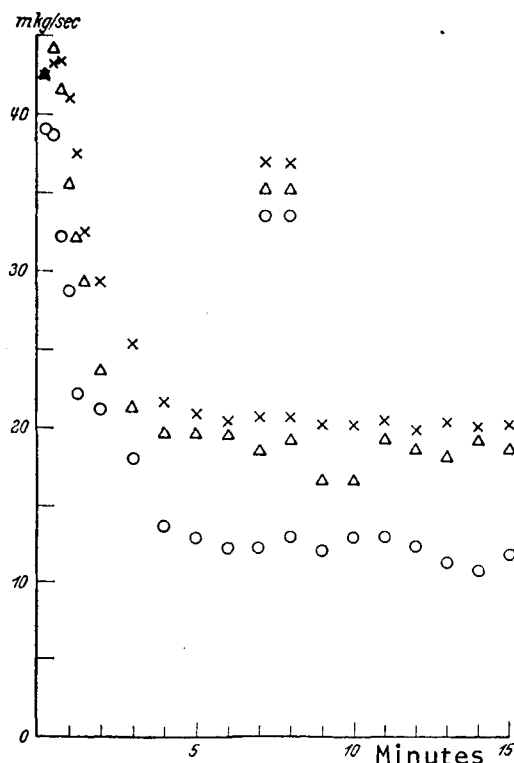


Figure 1. Test Person Gol.

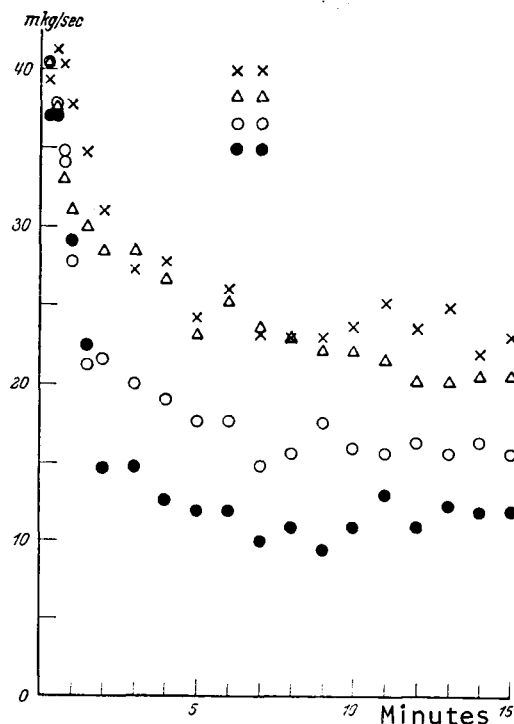


Figure 2. Test Person Mar.

At the beginning of the work periods, the work curves gained at the various pressures are completely congruent, which is probably connected with the fact that the released energy originates for the most part from anaerobic cleavages which occur in the muscles and consequently is to a certain degree

independent of the oxygen pressure. Later, however, as long as there is no recuperation of the muscle through oxidative processes, no further work output can occur; this is therefore quantitatively limited by the oxygen then available. In fact, we see that with the reduction of the atmospheric, and consequently also the oxygen, pressure the curve falls off much more quickly and sharply, to adjust itself to an approximately constant value; this value is significantly lower than at normal barometric pressure.

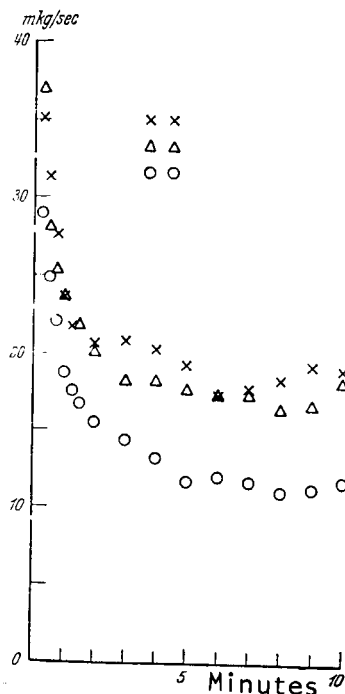


Figure 3. Test Person Gya.

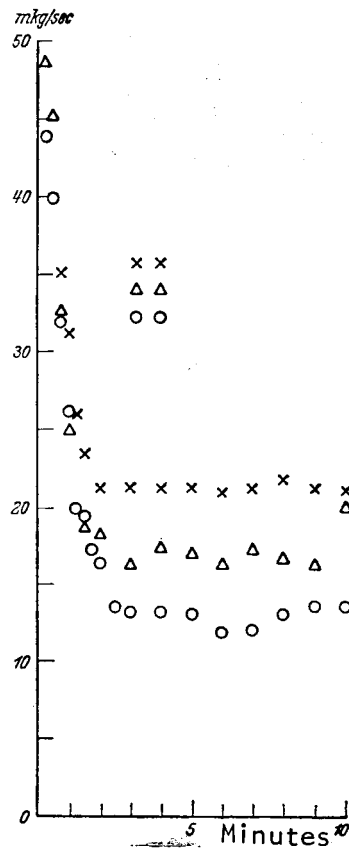


Figure 4. Test Person Man.

Perhaps the most interesting result of these curves is just this value, which the output assumes a certain time after the beginning of the work, a value which can be maintained constant for several minutes and which we can with sufficient accuracy (all the more since it is a relative value) consider as the output which the organism is capable of developing over an infinite time.

If we postulate the output which is developed by an individual at normal atmospheric pressure in the phase of constant work as equal to 100, we receive the values summarized in the following table, which has been drawn from the mean values of the curve in Figure 5 for the decreased pressure.

TABLE 1

Pressure	740	540	400	313
Gol.	100	90	58,5	0
Mar.	100	91 (90,6)	69,5	50 (43) (0 at 239 mm Hg)
Gya.	100	94	62	—
Man.	100	79	60	—
Mean	100	88,5 (88,7)	62,5	0 (18) (0 at 239 mm Hg)

(The values in parentheses are those which were calculated by means of the formula given in the text.)

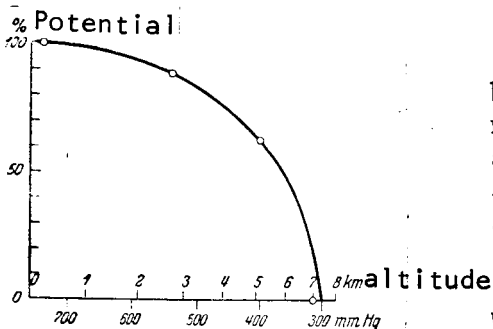


Figure 5.

It is clear from these curves that at the beginning, very significant pressure reductions must be made before the output declines noticeably; the curve then bends sharply at between 500 and 400 mm hg and then falls off very sharply at pressure values below 400 mm.

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I have attempted to calculate such a curve which corresponds with sufficient precision to the following formula for the three values x equals 740, 540, and 400:

$$y = \frac{b}{b - a(740 - x)^2};$$

in which b equals 10,000 and a equals 0.0527.

In this formula, b is nothing more than the square of the output developed at normal barometric pressure, which in our case was equal to 100. On the other hand, a increases with the bend of the curve and qualifies the value which the output assumes at each pressure; value a therefore expresses the individual decrease in capability to perform a task at a retarded barometric state.

The possibility of expressing the course of the phenomena with a formula which is also valid for the lower value of x is important in that we can thereby calculate at what pressure the capability to perform constant and voluntarily rhythmical work ceases.

It would follow from the above-given formula that work falls to zero at a pressure of 304 mm Hg (somewhat more than 7000 meters altitude), and that this pressure represents the limit at which on an average, muscular work can no longer be accomplished at all. Since we are not dealing with average value, but rather with these which we received from one of the test persons (Mar.), we have the value of 0.0447 for a; work incapacity did not occur for this test person until a pressure of 239 mm Hg, which represents an altitude of approximately 9200 meters.

We now wish to investigate how this rapid fall in work capability comes about with severe pressure reduction. There is no doubt that the cause, at least for the most part, is the decrease in oxygen pressure in the air and consequently in the blood; but does the effect of this decrease in pressure consist only of a decline in the oxidation process in the muscles, or is this fact insufficient to explain the observed phenomena?

We have seen that for significant pressure reductions the work curve remains almost constant in its beginning portion at almost all pressure values, since the work is accomplished at the cost of the energy collected in the muscles, without the participation of the oxygen. This work could be accomplished by the muscles even in a completely oxygen-free environment, as has already been demonstrated by Spallanzani, except that in the latter case the curve had a sharper decline and sank rapidly to the abscissa axis.

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In the present experiments, however, at a pressure which corresponded to an altitude of 7000 meters, 3 of the 4 test persons were in no condition to perform even the slightest work.

Therefore we must not look for the cause of the observed phenomena in the muscles alone. On the other hand it is apparent that a pathological state of the central nervous system caused by anoxemia occurs, whereby the former becomes incapable of creating and coordinating the stimulus which is supposed to cause the contractions in the muscles.

For this reason I have attempted to determine what fraction of the total work was conducted anaerobically. If we assume that the maximum output which a man can develop over an infinite period of time coincides with the highest possible output without need for oxygen, then the anaerobically accomplished work will be equal to the difference between the total work and the product of the output in the phase of constant work throughout the duration of the experiment.

I have determined the total work done in each experiment by the various test persons by measuring on the accompanying curve the area between the curve itself and the coordinate axis and from this, by means of the values extracted from the foregoing tables, have calculated the work which was accomplished anaerobically. If we postulate the anaerobically accomplished work at normal barometric pressure as being equal to 100, we receive the values summarized in the following table for the various pressures:

TABLE 2.

Pressure	740	540	400	313
Gol.	100	113	114	0
Gya.	100	101	151	—
Mar.	100	111	121	83
Man.	100	107	123	—
Mean . . .	100	108	127	0

It can be seen from the above table that the anaerobically accomplished work increases up to a certain limit with the decrease in pressure, but after passing this limit drops rapidly to zero. An increase in the anaerobically accomplished work at decreased pressure had already been observed by me through determination of the oxygen requirement after a prescribed amount of work [11]. It seems to me that the conclusion can be drawn from this that the effect of the pressure reduction first makes itself apparent, not through a reduction of the muscular work so that the muscles normally contract under the effect of normal stimulus of the nerve centers, but by an increase in the oxygen requirement, which then overloads the subsequent oxygen balance, whereby the work of the constant phase is decreased; in fact, the intensity of the nervous stimuli going to the muscles is not weaker than the stimuli occurring at normal pressure, since they cause muscle contractions even under adverse conditions of oxygen requirement just as under normal pressure.

The effect on the nerve centers would therefore only occur at lower pressure, and almost suddenly, so that it would cause a rapid decline of every muscle activity, especially if a brief muscular work has caused a further demand on the oxygen available to the organism, so that the nervous system, which has maintained itself at full stimulus over a long time, suddenly loses its capacity to generate any stimuli, while the muscle is still capable of work.

Therefore the anoxemia acts, as far as the reduction of work capability is concerned, on the muscles on one hand, in that it limits the oxidation taking place there, and on the central nervous system on the other.

These experiments do not permit us to determine how much of the observed reduction of work capability can be ascribed to one or the other. From the course of the curve represented in Figure 5 and from that which we have described, we can nevertheless conclude that the damaging influence exerted by the anoxemia on the nerve centers at massive reductions in pressure (at least up to about 500 mm Hg) can be completely ignored, and that the reduction in work capability observed up to this limit is in an overwhelming majority a result of the reduction of the quantity of oxygen available to the muscles. The effect of the oxygen shortage on the nerve centers then sets in quite suddenly, at a pressure of 300 to 400 mm Hg, at which every voluntary muscle activity becomes impossible.

Summary

Determination of the work capability of human beings at various atmospheric pressures was conducted.

It was observed that the capability to perform a constant maximum work decreased only slowly with the reduction in pressure, and then between 400 and 500 mm Hg (4000 to 5000 meters in theoretical altitude) declines sharply to zero at a pressure of about 300 mm Hg (corresponding to 7000 meters altitude).

The amount of work which is accomplished anaerobically in the voluntary muscles increases at first with the declining pressure up to about 400 mm Hg and then falls off suddenly to zero at slightly less pressure (300 mm Hg).

It can be concluded from the course of the experiments that the effect of the reduction of the oxygen pressure on the decline in work capability in the first phase must be regarded as a reduction in the oxidation processes in the muscles; only in a second phase, with an even more severe reduction in the partial oxygen pressure are the nerve centers almost suddenly drawn into sympathy, so that they are no longer capable of forming motor stimuli.

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